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Citation: AIP Conference Proceedings **1979**, 070019 (2018); doi: 10.1063/1.5044828
View online: https://doi.org/10.1063/1.5044828
View Table of Contents: http://aip.scitation.org/toc/apc/1979/1
Published by the American Institute of Physics

Pressure-Shear Plate Impact Experiment on Soda-Lime Glass at a Pressure of 30 GPa and Strain Rate of $4{\cdot}10^7\ \mathrm{s}^{-1}$

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Abstract. Recent modifications of a powder gun facility at Caltech have enabled pressure-shear plate impact (PSPI) experiments in a regime of pressures and strain rates that were previously unaccessible. A novel heterodyne diffracted beam photonic Doppler velocimeter (DPDV) has also been developed for simultaneous measurement of the normal and transverse particle velocity histories using the $\pm 1^{st}$ order diffracted beams produced by a 400 lines/mm diffraction grating deposited onto the polished rear surface of the impacted target plate. We present and interpret the results of a PSPI experiment conducted on a 5 μm thick soda-lime glass sample subjected to a normal stress of 30 GPa and a shear strain rate of $4 \cdot 10^7\ \mathrm{s}^{-1}$. Transverse particle velocity measurements reveal a peak shear stress level of 1.25 GPa up to a shear strain value of 2.2, followed by a precipitous drop in stress and complete loss of shear strength.

INTRODUCTION

The shearing resistance of materials depends on a number of parameters, such as the strain rate [1, 2] and pressure [3] that a material experiences during loading. Pressure-induced phase transformations add another level of complexity to characterizing the strength of materials, as structural changes on an atomistic scale may lead to very different material behavior. Hence, experiments have to be carried out over a wide range of conditions to develop reliable models for the simulation of dynamic loading events.

Gleason et al. [4] conducted laser-induced shock experiments on amorphous silica and observed a phase transformation towards a dense, crystalline phase called stishovite at pressures beyond 18.9 GPa. PSPI experiments constitute an excellent technique to investigate the effect of the stishovite phase transformation on the strength of silica glasses due to their well-characterized one-dimensional plane wave loading [1]. However, current PSPI setups rely on single-stage gas guns to accelerate their projectile and are limited to maximum normal stresses of approximately 20 GPa. Recent modifications of a powder gun at Caltech have enabled PSPI experiments at normal stresses of up to 75 GPa and shear strain rates approaching $10^8\ \mathrm{s}^{-1}$. This capability is employed to explore the dynamic strength of soda-lime glass under the conditions conducive to the reported phase transformation in [4].

EXPERIMENTAL SETUP

The PSPI technique requires a slotted gun barrel to prevent rotation of the sabot after alignment of the flyer and target plates. A 38 mm diameter powder gun barrel containing a broached rectangular keyway (3.2 mm width, 1.9 mm depth, 1.5 mm corner radii) permits the acceleration of sabots with inclined flyer plates to velocities ranging between 200 and

Shock Compression of Condensed Matter - 2017
AIP Conf. Proc. 1979, 070019-1–070019-5; https://doi.org/10.1063/1.5044828
Published by AIP Publishing. 978-0-7354-1693-2/$30.00

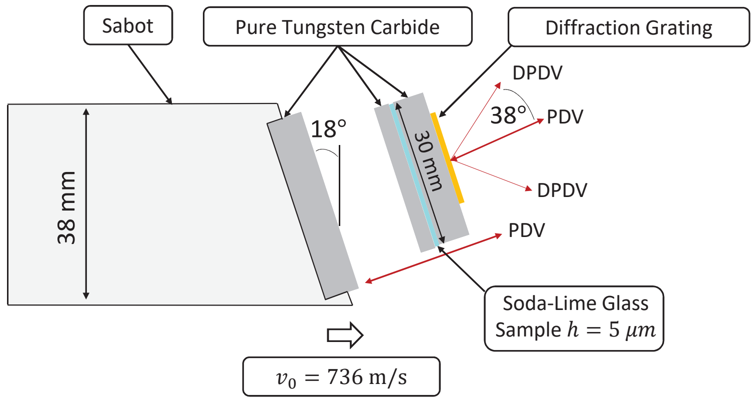


FIGURE 1. Schematic of PSPI setup with experimental parameters. DPDV (simultaneous normal and transverse particle velocity measurement) with independent PDV diagnostic (normal particle velocity measurement) and PDV impact velocity measurement

1800 m/s. A maximum impact velocity of 1800 m/s translates to a normal stress of $\approx$ 75 GPa using high impedance, pure WC flyer and anvil plates.

A schematic of the PSPI experimental setup is shown in Fig. 1. The flyer and target (anvil) plates were made from pure WC and inclined at an angle of 18° relative to the direction of approach. The pure WC anvil plates sandwich a 5 μm thick vapor deposited layer of soda-lime glass, covered by a 200 nm thick SiO_2 coating which was added to prevent moisture absorption. A 400 lines/mm gold diffraction grating was applied to the polished rear surface of the anvil plate assembly to efficiently diffract a normally incident λ = 1550 nm laser beam into a 0^{th} and $\pm 1^{st}$ order beams used by the PDV and DPDV arrangement depicted in Fig. 2. The 0^{th} order and $\pm 1^{st}$ order diffracted beams are each collected using custom fiber-optic probes specifically designed to address the anticipated loss of light at higher impact velocities. Symmetrically diffracted $\pm 1^{st}$ order beams are directed to the DPDV diagnostic for combined measurement of normal and transverse particle velocities, while the 0^{th} order beam is interfered by a PDV to obtain an independent measurement of the normal particle velocity [5]. A shifted-window discrete Fourier transform (DFT) algorithm is applied to extract the signal frequency variation from the acquired DPDV fringe records, which are then appropriately combined and scaled to obtain the normal and transverse velocity profiles [5]. Low transverse velocities in PSPI ex-

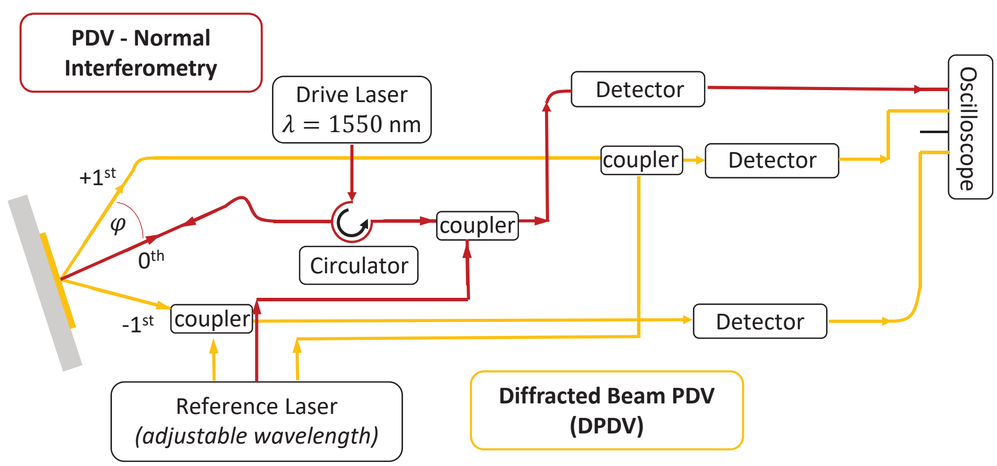
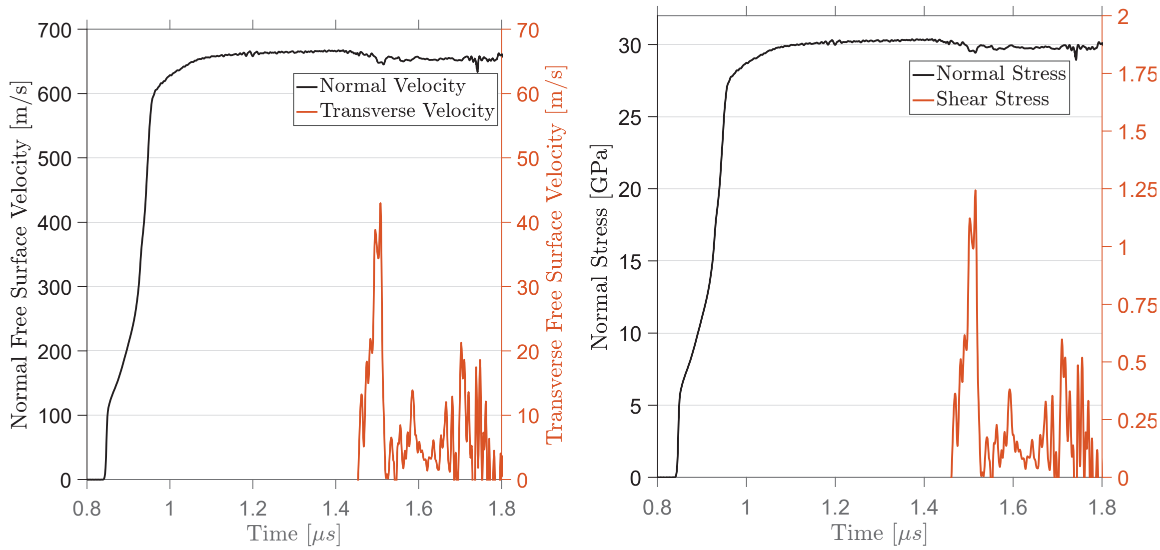


FIGURE 2. Schematic of PDV and DPDV diagnostic system, which relies on the interference of the 0^{th} and $\pm 1^{st}$ order diffracted beams with an adjustable wavelength reference laser for frequency conversion

periments produce correspondingly low signal frequencies that are impossible to analyze by a shifted-window DFT algorithm while providing a sufficient temporal resolution for PSPI experiments. The heterodyne scheme overcomes this challenge by shifting the signal frequency at zero velocity to 1.3 GHz, which enables the accurate determination of normal and transverse particle velocities with nanosecond time resolution [6] and provides automatic, unambiguous detection of velocity reversals. The effective DPDV measurement sensitivity to transverse velocity is controlled by the grating pitch and theoretically equivalent to that of a transverse displacement interferometer (TDI) [7]. The measurement sensitivity to normal velocity is increased by 1.78× compared to the sensitivity of the PDV using the 0^{th} order (reflected) beam [5].

EXPERIMENTAL RESULTS

The normal and transverse rear surface particle velocity profiles acquired from the DPDV fringe records are shown in Fig. 3(a). Corresponding normal and shear stresses on the glass sample interface, plotted in Fig. 3(b), were obtained using an experimentally validated strength model calibrated to stress levels exceeding the Hugoniot elastic limit (HEL) of pure WC [8]. The normal stress plot in Fig. 3(b) reveals the HEL of the WC anvil plates at 5.8 GPa, which is close to the pressure range (6.1-7.1 GPa) reported in other studies [9]. This is followed by a sharp rise to a stress level of 30 GPa as shown in Fig. 3(b). The shear stress curve exhibits a rapid climb to a peak value of 1.25 GPa and is followed by a sudden and rapid loss in shear strength.



(a) (b)

FIGURE 3. (a) Normal and transverse free surface velocity profiles measured by the DPDV diagnostic. (b) Inferred normal and shear stresses using an experimentally calibrated strength model for pure WC anvil plates [8]

Figure 4(a) compares the shear stress versus time profile obtained in the present experiment with two nearly identical experiments conducted by Jiao et al. [10] at lower normal stresses of approximately 9 GPa and shear strain rates of $8 \cdot 10^6$ s^{-1}. Plots of the shear stress as a function of accumulated shear strain for each of these experiments are depicted in Fig. 4(b). Although the peak shear stress observed in our experiment is reached in a shorter amount of time, the total shear strain is comparable to the strain reported by Jiao et al. [10]. A shear strain value of $1.5 - 2.2$ at peak shear stress, as depicted in Fig. 4(b), has also been observed in previously reported experiments and is attributed to a bond-switching mechanism between covalent Si-O bonds in this range of shear strain [11, 12].

Figure 5(a) provides an expanded view of the normal velocity profile measured by the DPDV diagnostic superimposed upon an independently measured normal velocity profile obtained by the PDV using the 0^{th} order reflected beam. Close examination of the two nearly perfectly superimposed curves reveals an inflection, which occurred at approximately 0.93μs as the particle velocity crossed the 350 m/s threshold. Finite element simulations using the aforementioned strength model of WC revealed that this wave structure can be attributed to the interaction between

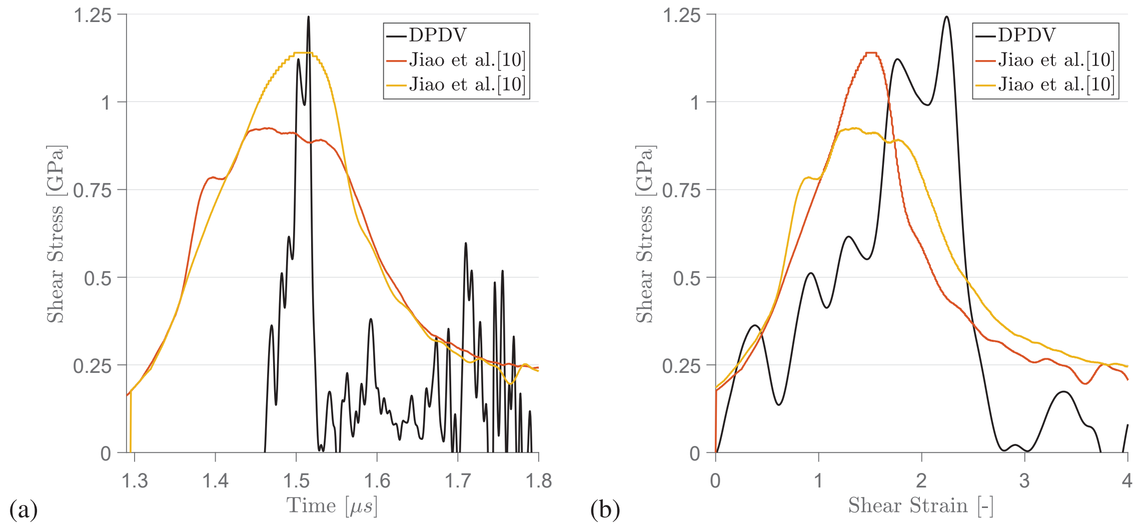


FIGURE 4. Comparison of shear stress as a function of (a) time and (b) shear strain in the present experiment with two experiments conducted by Jiao et al. [10] at lower normal stresses of 9 GPa and shear strain rates of $8 \cdot 10^6$ s^{-1}

the reflection of the elastic precursor from the rear surface of the target assembly and the plastic wave before reaching the free surface. Figure 5(b) depicts the corresponding normal stress profiles that follow from the experimentally validated strength model.

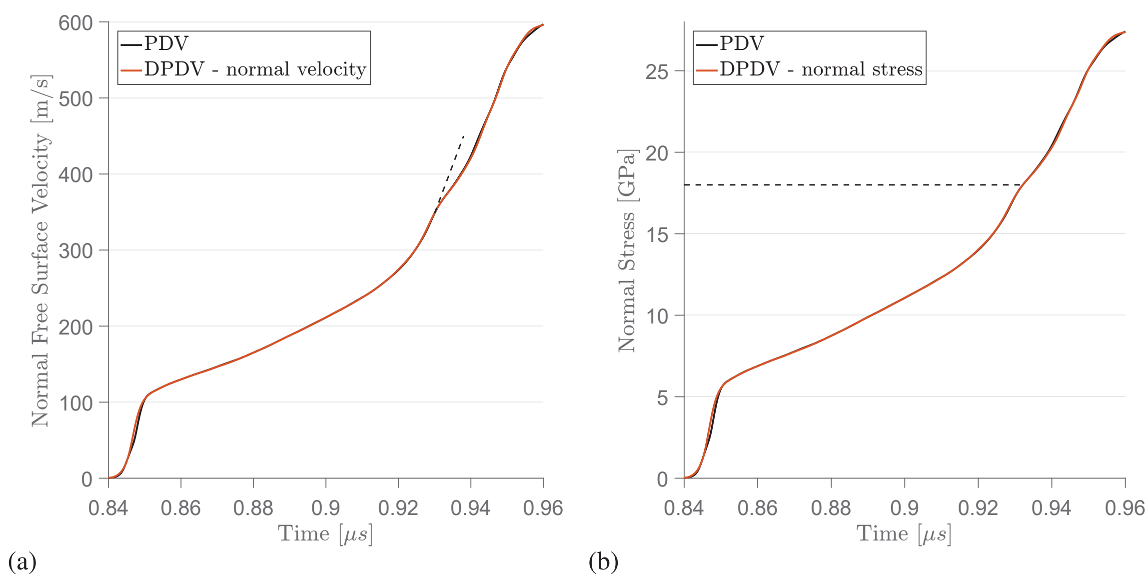


FIGURE 5. Detailed view of the (a) normal velocity profile in Fig. 3(a) measured independently with PDV and DPDV diagnostics and (b) inferred normal stress based on the PDV and DPDV measurement. A wave structure between the elastic and final plastic wave, associated with the interaction of the elastic precursor and plastic wave, is observed at an inferred normal stress of 18 GPa

CONCLUSIONS

Results are presented from a PSPI experiment conducted on a 5μm thick soda-lime glass sample conducted at an unprecedented pressure (30 GPa) and strain rate ($4 \cdot 10^7$ s^{-1}). Normal and transverse particle velocities were measured using a newly developed heterodyne diffracted beam photonic Doppler velocimeter (DPDV) and a complimentary PDV arrangement, which provided an independent measurement of the normal particle velocity. Normal and shear stress profiles were inferred using an experimentally calibrated strength model of the pure WC anvil plates [8], which sandwiched the thin glass specimen. The shear stress observed in the experiment quickly reached its maximum value of 1.25 GPa after which a sudden loss of shear strength occurred. Comparisons to previous experiments conducted at lower pressures by Jiao et al. [10] showed a similar shear strain level ($1.5 - 2$) at which this maximum shear stress is achieved.

ACKNOWLEDGMENTS

The authors are grateful for support from the Office of Naval Research (Award No. N00014-16-1-2839) for the development of the PSPI capability at high pressures and the Air Force Office of Scientific Research (Award No. FA9550-12-1-0091) for development of the PDV-DPDV interferometer system.

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